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Pilot's Attention Distributions between Chasing a Moving Target and a Stationary Target

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ABSTRACT

Introduction: Attention plays a central role in cognitive processing; ineffective attention may induce accidents in flight operations. The objective of current research was to examine military pilots' attention distributions between chasing a moving target and a stationary target. **Method**: Thirty-seven mission-ready F-16 pilots participated in the current research. Subjects' eye movements were collected by a portable head-mounted eye-tracker during tactical training in a flight simulator. The scenarios of chasing a moving target (air-to-air) and a stationary target (air-to-surface) consist of three operational phases; searching, aiming and lock-on to the targets. **Results**: The findings demonstrated significant differences in pilots' percentage of fixation during searching phase between air-to-air (M=37.57, SD=5.72) and air-to-surface (M=33.54, SD=4.68). Fixation duration can indicate pilots' sustained attention to the trajectory of a dynamic target during dog-fight manoeuvers. Aiming for the stationary target with larger pupil size (M=27105 pixel^2, SD=6565 pixel^2) reflects higher cognitive loading than aiming to the dynamic target (M=23864 pixel^2, SD=8762 pixel^2). **Discussion**: Pilots' visual behavior is not only closely related to attention distribution, but also significantly associated with task characteristics. Military pilots demonstrated various visual scan patterns for searching and aiming to different types of targets based on the research settings of flight simulator. The findings would facilitate system designers' understandings of military pilots' cognitive processes during tactical operations. It will assist human-centered interface design to improve pilots' situational awareness. The application of an eye-tracking device integrated with a flight simulator is a feasible and cost-effective intervention to improve efficiency and safety of tactical training.

Keywords: attentional processes; eye movements; mental workload; simulation and training; situation awareness

INTRODUCTION

Pilots have to process information based on interior cockpit indicators and the exterior environmental stimuli by visual search during flight operations. Compared with commercial flight, exterior stimuli for military pilots also include either the moving target of a foe or a stationary surface target. Lavine, Sibert, Gokturk, and Dickens (12) suggest that visual attention is a precursor to initiate the cognitive process and information acquired from pilot’s visual scan is closely associated with a pilot’s attention allocation. Ineffective attention distribution may induce accidents (e.g., Asiana Airlines Flight 214 which crashed on final approach), as pilots’ lack of situation awareness to the airspeed indicator was a critical human factors issue in the accident (17). Attention plays a central role in cognitive processing. How and where pilots distribute attention is critical to the quality of situational awareness (SA) and links to the features of individual's expectations (7). Therefore, eye movements may serve as a window to illustrate pilots’ attention distribution and mental state during flight operations (13). The pattern of pilots’ eye movement is one of the methods for assessing pilots’ cognitive processes, based on real-time physiological measures (1). Therefore, pilots’ visual behaviors are indicators to reveal attentional distributions during flight operations (9, 21).

Fixation is defined typically as the eye movement pausing over informative regions of interest. Human beings usually retain fixations on the objects to acquire the most essential information to support the task in hand (21). The patterns of fixations on the indicators or the areas of interest (AOIs) can reveal a pilot’s visual trajectory of attention (23). Moreover, the percentage of fixations on the relevant AOIs is deemed as the predictor of the overall SA performance (15). In addition, the length of fixation duration is the total time fixating on an AOI, which can reflect the level of importance or difficulty in extracting information (2). Fixation duration might reveal how long pilots sustain attention whilst scanning the visual fields in order to complete the mission. On the other side, fixation duration might be an index of cognitive capture or over-concentration on a specific indicator, which will slow down attention shifts to the tactical situation (7).

Pupil dilation is known to quickly respond to changes in the illumination in the visual field and to a human being's perceived workload while performing a visual task. Under controlled illumination, the pupil size is an effective and reliable indicator of mental workload. The increasing in pupil size is correlated with the increasing in mental workload (6). Attention is critical to pilots filtering the stimuli to the perceptual system. However, workload usually has negative impacts to the effectiveness of visual attention (14). The increasing pupil size is a physical feature of cognitive load (19), as it can be an important indicator of a pilot's cognitive process and visual attention (23).

Saccadic eye movements are controlled by top-down visual processes, which are coordinated closely with perceptual attention (24). It indicates that saccadic paths are intentional and meaningful based on the requirements of the task in hand and the trajectory prediction in the near future (11). Therefore, the path of saccades is associated with selective attention and accurate judgments for perceptual targets (4, 16). Saccade duration is the total time taken to make a saccade, which is recognized as one of indexes to assess operator's workload; e.g., increase in workload has been found to decrease saccade duration (20). Saccade velocity is how fast the eyes move between fixations, which are associated with rapid deployment of attention. Thus saccades might be an effective indicator of attention distribution.

The information provided in the cockpit is mostly acquired by pilots' visual scans among cockpit interfaces, and previous research has shown that 75% of pilot errors result from poor perceptual encoding (3, 8). It highlights the importance of the interactions between pilots' visual scan and the characteristics of cockpit interface design. It is obviously that attention is a critical precursor to in-flight SA performance and decision-making (18). Eye tracking has been gaining in popularity over the past decade as a window into participants' visual and cognitive processes. Therefore, analysis metrics of current research include five parameters of visual behavior: the percentage of fixations, fixation duration, pupil size, saccade duration, and saccade velocity among three operational phases composed with searching for visual contact with a target, aiming at a target, and lock-on for pick-off (press the trigger to launch weapon) between air-to-air for a moving target and air-to-surface for a stationary target. Based on the above literature review, there are four fundamental hypotheses will be investigated as followings: (1) there is no significant difference in pilots' fixation duration between chasing a moving target and a stationary target; (2) there is no significant differences in pilots' fixation duration among three operational stages; (3) there is no significant difference on pilots' pupil dilation between chasing a moving target and a stationary target; (4) there is no significant differences on pilots' saccade velocity among three operational stages.

METHODS

Aims

The research aims were (1) to investigate pilots' visual characteristics between pursuing a moving and a stationary target; (2) to explore pilots' eye movement patterns and attention distributions on three operational stages, searching, aiming and lock-on a target; (3) to evaluate pilots' pupil dilation and cognitive process on three operational stages between the pursuit of a moving and a stationary target; and (4) to apply the findings to benefit military pilot training and cockpit interface design.

Subjects

A total of thirty-seven qualified mission-ready F-16 pilots participated in this research. The subjects' flying experience varied between 372 and 3,200 hours (M=1280, SD=769). The ages ranged between 26 and 45 years old (M=33, SD=5). All of the subjects were male volunteers and informed that they had the right to cease the experiments and withdraw information they provided without any reason. Subjects signed an informed consent form and reported normal levels of visual function. The treatment of all subjects complied with the ethical standards required by the Research Ethics Regulations of Cranfield University.

Equipment

Flight Simulator: The flight simulator used in the experiment is a formal F-16 trainer. It is a high-fidelity and fixed-base type flight simulator. It consists of identical cockpit displays to those in the actual aircraft to supports pilots' routine flight training and combat planning. It is integrated with high-definition databases, image generation systems and physics-based processing technology which enable pilots to detect, judge the orientation of, recognize and identify targets as they would in the real world of tactical operations. The instructor can install scenarios and observe the trainee pilot's performance via a console with three monitors.

Eye Tracking Device: Pilots' eye movement data were collected by a mobile head-mounted eye-tracker which is designed by Applied Science Laboratory (ASL Series 4000). It is portable and light (76 g) so participants can move their head without any limitations. The sampling frequency of this type of eye-tracker is 30 Hz. Video recordings of eye movements and the related data were collected and stored using a Digital Video Cassette Recorder (DVCR) and then transferred to a computer for further analysis. The definition of an eye fixation in the present study was as three gaze points occurred within an area of 10 by 10 pixels with a dwell time more than 200 msec (21).

Scenarios

Air-to-Air Task for Pursuing a Moving Target: The scenario-1 is an air-to-air (A-A) manoeuver to pursue a dynamic target. The altitude of the interceptor (participant) at the patrol area was 20,000 feet with a cruise speed of 300 knots indicated airspeed (KIAS). The heading was 050° under the weather conditions of 7-mile visibility and scattered clouds. A foe unexpectedly appears at the same altitude as the target moving from left to right with heading of 090° and air speed of 300 KIAS. The participants have to search the airspace for the target, and intercept the target immediately by tactical manoeuvers. At the same time, the target would change its heading, altitude and speed in order to escape from the interceptor's pursuit (figure 1a).

[Figure 1 here]

Air-to-Surface Task for Aiming at a Stationary Target: The scenario-2 is an air-to-surface (A-S) manoeuver to pursue a stationary target. Participants were dispatched unexpectedly to attack one stationary target, where they not only needed to execute tasks precisely by operating the aircraft, but also to follow the navigation system, entering appropriate codes by using various cockpit interfaces. Participants had to intercept the proper route and turn toward the target at an altitude of 500 feet with a speed of 500 KIAS simultaneously, then performed a steep pop-up manoeuver to increase altitude abruptly for appropriate target reconnaissance, followed by a dive and roll-in toward the surface target to avoid hostile radar lock-on. When approaching the target, participants have to roll-out, level the aircraft, aim at the target, lock-on and pick-off the target (figure 1b).

Research Design

Procedures: All participants undertook the following procedures; (1) complete the demographical data including rank, job title, age, education level, qualifications, type hours and total flight hours (5 minutes); (2) a short briefing explaining the purpose of the study and the introduction of the air-to-air and air-to-surface scenarios without mentioning any potential aircraft equipment failure (20 minutes); (3) participants were seated in the F-16 simulator and then the eye-tracker was put on for calibration using three points distributed over the cockpit display panels and outer screen (15-25 minutes); (4) perform the air-to-air task for aiming at a dynamic target (5 minutes); (5) perform air-to-surface task for aiming at a stationary target on the ground (5 minutes); simultaneously the instructor pilot in the simulator console evaluated participants' performance. It took around 60 minutes for each participant to complete the experiments.

Analysis of Eye Movements Data: The eye movement data of both air-to-air and air-to-surface tasks in this study were analyzed by three phases of visual behavior during tactical operations: searching for the target with eye contact (Searching), pursuing the target for aiming (Aiming), and lock-on to the target for pick-off (Lock-on). The length of time for analyzing each operational phase was 6 seconds (18 seconds in total for three phases). It was grounded by the consensus of experienced instructor pilots based on the most critical decisive time to process tactical information during performing both air-to-air and air-to-surface tasks. The variables of eye movement data were analyzed by percentage of fixation, fixation duration, pupil size, saccade duration and saccade velocity.

RESULTS

The demographical information of participants' age, rank, qualification and total flight hours are shown as table I. As percentage of fixation is proportional data, it is necessary to perform an arcsine transformation in advance to enable further statistical analysis (5). Based on the research design of current study, a paired T-test and ANOVA were applied to analyze the differences of eye movement data between air-to-air and air-to-surface during three operational phases of searching, aiming and lock-on (dependent variables). The analysis for this study is a within subjects test, as all participants were performing both tactical tasks of aiming at a dynamic target (air-to-air) and a stationary target (air-to-surface).

[Table I here]

There were five dependent variables related to pilots' eye movement characteristics between air-to-air and air-to-surface tasks among three operational phases, which are fixations/ percentage of fixation, fixation duration, pupil size, saccade duration, and saccade velocity. The results demonstrated that there were significant differences in pilots' fixations (t=-2.52, p<.05, d=-.624) and fixation duration (t=3.26, p<.005, d=.748) between air-to-air and air-to-surface task. Therefore, the null hypothesis 'there is no significant differences on pilots' fixation duration between chasing a moving target and a stationary target' was rejected. Also, there were significant differences in pilots' saccade duration between the two tasks, t=-2.30, p<.05, d=-.372. However, there were no significant differences in pilots' pupil size (t=-1.92, p>.05, d=-.252) and saccade velocity (t=-1.31, p>.05, d=-.214) between two tasks (table II).

[Table II here]

Significant differences among three operational phases were observed in terms of percentage of fixation during air-to-air, F (2, 36) =5.75, p<.01, $\eta 2\rho$ =.138, and air-to-surface, F (2, 36) =6.29, p<.01, $\eta 2\rho$ =.149. Further comparisons by post-hoc Bonferroni adjusted tests showed that during air-to-air task, searching (37.57) has a higher percentage of fixations than aiming (35.11), and lock-on (32.94); the highest percentage of fixations was occurred at aiming phase during air-to-surface. There were significant differences in pilots' fixation duration among three operational phases at air-to-air, F (2, 36) = 5.39, p<.01, $\eta 2\rho$ =.130, and also at air-to-surface, F (2, 36) = 18.48, p<.001, $\eta 2\rho$ =.339. Further comparisons by post-hoc Bonferroni adjusted tests showed that lock-on (938 msec) has significantly longer fixation duration than aiming (702 msec) and searching (612 msec) during air-to-air task; the patterns showed at air-to-surface was same as air-to-air, lock-on the longest fixation duration (580 msec), then aiming (462 msec) and searching (332 msec) (table III). Therefore, the null hypothesis 'there is no significant differences on pilots' fixation duration among three operational stages' was rejected.

[Table III here]

There were significant differences in pilots' pupil dilation among three phases during air-to-air, F (2, 36) = 7.57, *p*<.01, *η2ρ* = .174, and air-to-surface, F (2, 36) = 38.82, *p*<.001, *η2ρ* = .519. Further comparisons by post-hoc Bonferroni adjusted tests showed that pilots' largest pupil size at air-to-air was in the phase of lock-on (26147 $pixel^2$); the largest one at air-to-surface was occurred in aiming (27105 $pixel^2$). Therefore, the null hypothesis 'there is no significant differences on pilots' pupil dilation between chasing a moving target and a stationary target' was rejected.

There were significant differences in pilots' saccade velocity among the three phases during air-to-surface tasks, F (2, 36) =7.87, p<.01, η2ρ =.179. Further comparisons by post-hoc Bonferroni adjusted tests showed that pilots' saccade velocity during air-to-surface task at the phase of lock-on (1148 pixels/sec) was significantly longer than at aiming (1045 pixels/sec) and at searching (829 pixels/sec). However, there were no significant differences in pilots' saccade velocity among three phases during air-to-air task, F (2, 36) =.68, p>.05, η2ρ =.019 (table III). Therefore, the null hypothesis 'there is no significant differences on pilots' saccade velocity among three operational stages' was partially rejected.

DISCUSSION

The characteristics of the air-to-air task in current study are engaging a dynamic target by visual searching to aim and lock-on the moving target. On the other hand of air-to-surface, pilots have to perform a steep pop-up manoeuver to search for the target, followed by a rapid dive and roll-in to aim and lock-on the stationary target. The results showed the significant differences in pilots' fixations and fixation duration between the pursuit of a moving and a stationary target (table II). Pilots did demonstrate different patterns of fixations and fixation duration between chasing a moving target and stationary target. Furthermore, pilot's in-flight cognitive process is extremely dynamic, which needs to be explored by the contexts of operational environment.

Two different tactical tasks in current study are composed with three operational phases; each phase has specific tactical requirements and threats. Table III shows pilots distributed the highest percentage of fixations on aiming at the surface target (37.62 arcsine values). It reflects the tactical standard operating procedures that pilots have to precisely aim at the surface target within the time frame (between 3-5 seconds), otherwise the mission would be aborted. On the other side, searching a moving target at air-to-air task represents the highest percentage of fixations (37.57 arcsine values), which demonstrates that the uncertain trajectory of a moving target might increase pilots' cognitive load in searching for the unknown airborne target.

Pilots' fixation duration during the air-to-air task was significantly longer than the air-to-surface task across all phases (table III). It might indicate that pilots have to sustain substantial attention to avoid missing the trajectory of a dynamic target during the high kinetic manoeuvers. Especially the interval (236 msec) from aiming to lock-on, pilots' fixation duration increased 2.6 times compared to the interval from searching to aiming (90 msec). It reveals that pilots have to keep tracking and precisely project the target's probable trajectory movement in the vast airspace while aiming and locking-on a dynamic target.

[Figure 2 here]

Figure 2 indicates that pilots' pupil size in the phase of lock-on (26,147 pixel^2) is the greatest at the pursuit of a moving target. Also, the tendency of increasing pupil dilation along task performance might reveal pilots' increasing cognitive load from searching to lock-on. However, the pupil size at the pursuit of a stationary target is averagely greater than at the moving target. Figure 2 also shows the greatest pupil size was occurred at the aiming phase. The results did reveal there are significant differences on pilots' pupil dilation among three operational stages. Also, the increasing in pupil dilation from searching to aiming during the air-to-surface (3,108 pixel^2) is significantly greater than air-to-air (1,904 pixel^2). It shows that pilots might have tremendous cognitive workload during the air-to-surface task compared with air-to-air. The findings are constructive to comprehend pilots' cognitive processes regarding the aspect of workload objectively while chasing a stationary target with potential accident of control flight into terrain (CFIT) (10).

[Figure 3 here]

The significant difference in pilots' saccade duration was observed between the air-to-air and air-to-surface tasks (table II).

Figure 3 reveals that pilots significantly decreased time to make a saccade while searching a dynamic target (239 msec) than searching for a stationary target (457 msec). It illustrated that pilots shifted attention with shorter time to search for an almost unknown and moving target than for a stationary target with awareness of approximate location. As a result, the level of knowledge of the target influences pilot's saccade duration. In addition, the saccadic duration is accompanied by a shift of attention to the selected target (11). Searching for the stationary surface target seems to reflect higher cognitive load than searching for the dynamic target (20). Pilots operating fighter aircraft towards a surface target must fly so precisely in order to avoid the accident of CFIT. Simultaneously, they also have to be aware of hostile threats while assessing appropriate timing for lock-on and pick-off. It was found that the decreasing rate at saccade duration from searching to aiming during the air-to-surface task is 55.36% (figure 3).

[Figure 4 here]

There was no significant difference between two tasks although table II reveals average saccade velocity at the pursuit of a stationary target (1007 pixels/ sec) is faster than the pursuit of a moving target (948 pixels/ sec). However, there were significant differences among three phases during the air-to-surface task (table III). Figure 4 reveals the fastest saccade velocity was occurred at the lock-on phase (1148 pixels/sec). In contrast, the slowest saccade velocity is at the searching phase (829 pixels/sec) which is the stage of collecting relevant navigation and target information for further operations. Processing massive amounts of information inducing high cognitive load might be the reason to make the searching phase demonstrating the slowest saccade velocity and the longest saccade duration. In addition, the fastest saccade velocity reveals the lock-on phase requiring quick attention shifts to enhance situational awareness as flying at extreme low altitude for air-to-surface task. The findings of saccade duration and saccade velocity reveal pilots' top-down visual scan patterns in tactical operations based on pilots' expectations (projection of the course of action) associated with specific objectives which are matched with the previous research (4, 22).

CONCLUSION

Current research found that pilots would apply different approaches of visual scan patterns for searching and lock-on to different types of targets. Eye tracking devices can aid in capturing a pilot's attention allocation where traditional flight simulators training were lacking. Additionally, the analysis of eye movement parameters in real-time tactical manoeuvers could provide system designers with a better understanding of the tendency of pilots' cognitive process to optimize interface design and alleviate pilots' workload. The findings of current research also could facilitate the development of tactical training syllabi for air-to-air and air-to-surface tasks to improve pilots' attention distribution and situational awareness. However, the present findings were based on experiments conducted in a ground-based flight simulator. In order to reflect military pilots' in-flight cognitive process, next step is to develop a cockpit eye tracker to further study pilots' eye movement patterns and attention distributions in real tactical operations.

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TABLE I

Variables	Groups	Frequencies
Age	25-30	13 (35.1%)
	31-35	11 (29.7%)
	36-40	7 (18.9%)
	41-45	6 (16.2%)
Rank	Lieutenant	1 (2.7%)
	Captain	16 (43.2%)
	Major	9 (24.3%)
	Lieutenant Colonel	10 (27%)
	Colonel Above	1 (2.7%)
Qualification	Combat ready	13 (35.1%)
	Two fighter team leader	4 (10.8%)
	Four fighter team leader	9 (24.3%)
	Daytime back seat instructor	2 (5.4%)
	Training instructor	9 (24.3%)
Total Flight Hours	500 and less	3 (8.1%)
	501-1000	13 (35.1%)
	1001-1500	11 (29.7%)
	1501-2000	4 (10.8%)
	2001 and above	6 (16.2%)

TABLE I. SUBJECTS' DEMOGRAPHIC VARIABLES.

TABLE II

Variables	Tasks	M	SD	N	*T-Test*				
					t	*df*	*p*	*SE*	*Cohen's d*
Fixations	AA	8.0	2.2	37	-2.521	36	**.016**	0.44	-0.624
	AS	9.2	1.6						
Fixation duration (msec)	AA	751	543	37	3.263	36	**.002**	89.67	0.748
	AS	458	111						
Pupil size ($pixel^2$)	AA	23990	7703	37	-1.922	36	.063	913.33	-0.252
	AS	25746	6173						
Saccade duration (msec)	AA	196	215	37	-2.297	36	**.028**	30.82	-0.372
	AS	267	163						
Saccade velocity (pixels/sec)	AA	948	319	37	-1.308	36	.199	45.60	-0.214
	AS	1007	224						

TABLE II. T-TEST of EYE MOVEMENT VARIABLES between AIR-to-AIR (AA) and AIR-to-SURFACE (AS).

TABLE III

Variables	Tasks	Phases	*M*	*SD*	*df*	*F*	*p*	*η2ρ*
Percentage of fixations (arcsine values)	AA	S	37.57	5.72				
		A	35.11	2.96	36	5.75	**.005**	.138
		L	32.94	5.37				
	AS	S	33.54	4.68				
		A	37.62	3.93	36	6.29	**.003**	.149
		L	34.23	4.35				
Fixation duration (msec)	AA	S	612	487				
		A	702	515	36	5.39	**.007**	.130
		L	938	881				
	AS	S	332	71				
		A	462	145	36	18.48	**.000**	.339
		L	580	270				
Pupil size ($pixel^2$)	AA	S	21960	10132				
		A	23864	8762	36	7.57	**.001**	.174
		L	26147	6449				
	AS	S	23997	6180				
		A	27105	6565	36	38.82	**.000**	.519
		L	26136	6152				
Saccade duration (msec)	AA	S	239	332				
		A	167	188	36	1.34	.269	.036
		L	183	270				
	AS	S	457	288				
		A	204	198	36	29.06	**.000**	.447
		L	141	170				
Saccade velocity (pixels/sec)	AA	S	970	438				
		A	983	438	36	0.68	.510	.019
		L	891	437				
	AS	S	829	368				
		A	1045	328	36	7.87	**.001**	.179
		L	1148	394				

TABLE III. ANOVA of EYE MOVEMENTS at THREE OPERATIONAL PHASES: SEARCHING (S), AIMING (A) and LOCK-ON (L) during the TASKS of AIR-to-AIR (AA) and AIR-to-SURFACE (AS).

FIGURE 1

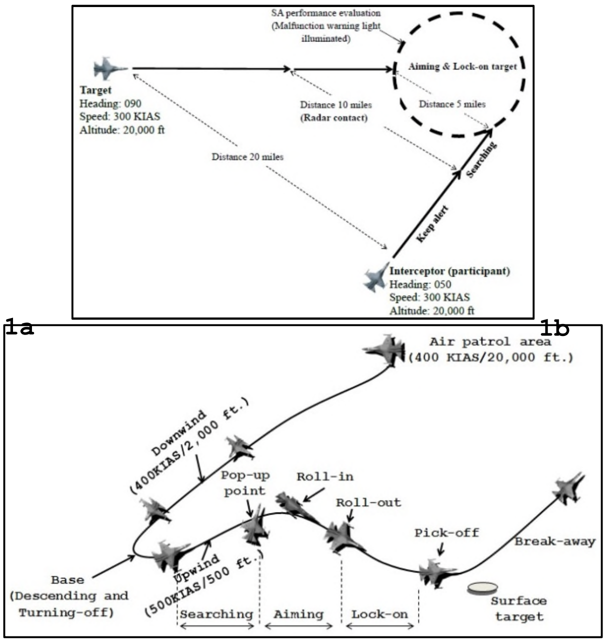

FIGURE 1. ILLUSTRATIONS of AIR-to-AIR (1a) and AIR-to-SURFACE (1b) TASKS

FIGURE 2

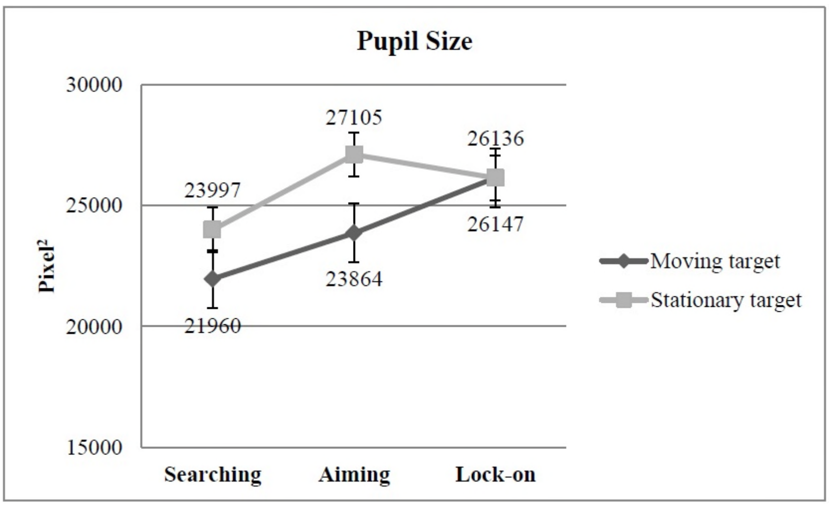

FIGURE 2. PILOTS' PUPIL DILATION among THREE OPERATIONAL PHASES WHILE PURSUING a MOVING TARGET and STATIONARY TARGET. THE BIGGEST PUPIL DILATION IS DURING the AIMING PHASE WHEN PURSUING a STATIONARY TARGET INDICATED the HIGHEST WORKLOAD.

FIGURE 3

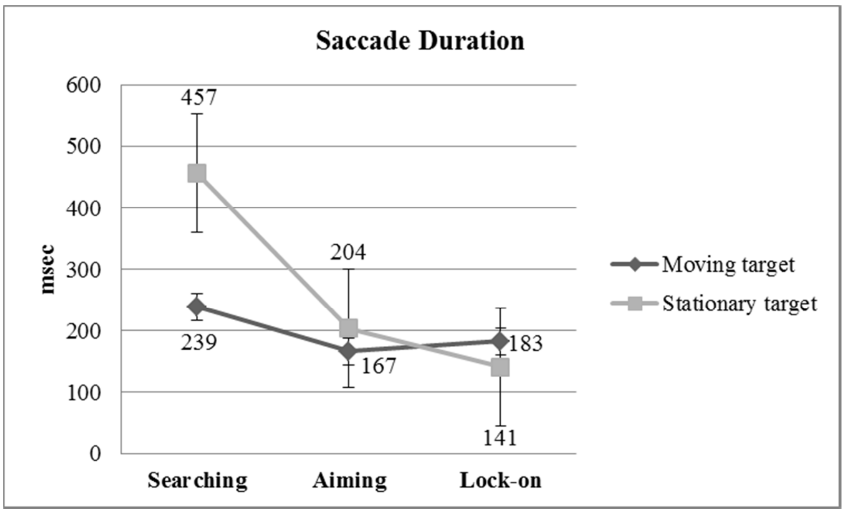

FIGURE 3. PILOTS' SACCADE DURATION at THREE OPERATIONAL PHASES WHILE PURSUING the MOVING TARGET and the STATIONARY TARGET. SEARCHING PHASE SHOWS the LONGEST SACCADE DURATION for BOTH TASKS, and PURSUING STATIONARY TARGET DEMOSTRATED SIGNIFICANT LONGER SACCADE DURATION THAN MOVING TARGET at SEARCHING PHASE.

FIGURE 4

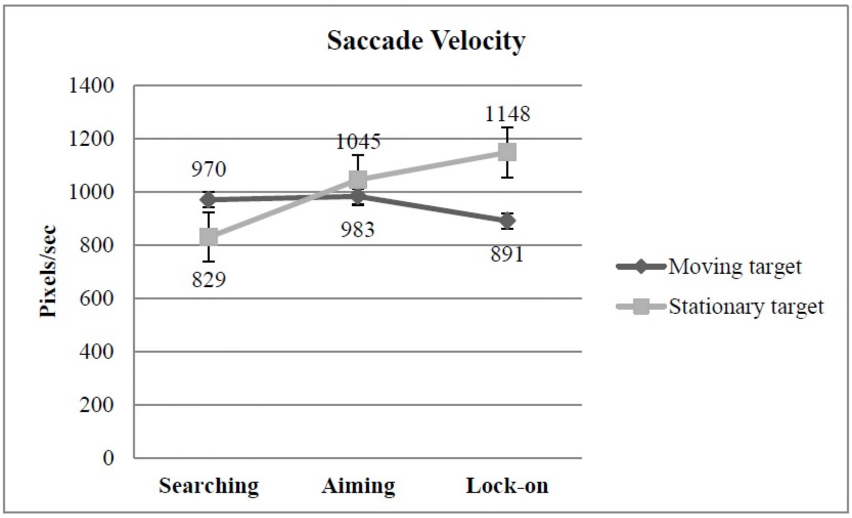

FIGURE 4. PILOTS' SACCADE VELOCITY at THREE OPERATIONAL PHASES WHILE PURSUING the MOVING TARGET and the STATIONARY TARGET. THE FASTEST SACCADE VELOCITY OCCURS at the LOCK-ON PHASE on PURSUING a STATIONARY TARGET. IT IS SIGNIFICANTLY FASTER THAN PURSUING a MOVING TARGET.

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chasing a moving target and a
stationary target

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